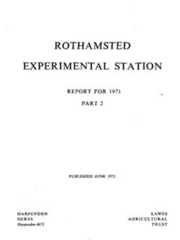
Rothamsted Experimental Station Report for 1971 Part 2



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The Agdell Experiment, 1848-1970 Estimates of the P and K Accumulated from Fertiliser Dressings Given Between 1848 and 1951, Their Recovery by Grass Between 1958 and 1970, and Their Effect on the Response by Grass to New Dressings of P and K

A. E. Johnston and A. Penny

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The Agdell Experiment, 1848–1970

Estimates of the P and K accumulated from fertiliser dressings given between 1848 and 1951, their recovery by grass between 1958 and 1970, and their effect on the response by grass to new dressings of P and K

A. E. JOHNSTON and A. PENNY

Increased agricultural production during the 18th and early 19th centuries owed much to the practice of growing crops in rotation. To try to explain some of these benefits, Lawes and Gilbert started a rotation experiment on Agdell Field in 1848, to compare with others in which the same crop was grown each year. On six large plots they tested two crop rotations, only one phase each year, and three manurial treatments. One rotation was the traditional Norfolk 4-course:

roots, barley, clover or beans, winter wheat (the 'clover rotation');

in the other the legume was replaced by a fallow:

roots, barley, fallow, winter wheat (the 'fallow rotation').

The roots were swedes or turnips, variety as on Barnfield, the varieties of barley and of winter wheat were those used on Hoosfield and Broadbalk. The clover was usually undersown in the barley on appropriate plots; when it failed, it was replaced by spring beans. The three manurial treatments were: unmanured (plots 5 and 6); P only, changed to PKNaMg in 1884 (plots 3 and 4); and NPKNaMg (plots 1 and 2), the N was given as a mixture of ammonium salts and rape cake, which also supplied some P and K. In contrast to the other Classical experiments in which the same manures were applied every year, only the root crops were manured in the Agdell experiment. In the Norfolk 4-course rotation some of the nutrients applied for the roots were recycled by sheep eating the crop on the land, and Lawes and Gilbert compared this on half plots with the other halves from which the crop was removed. The weather was often unsuitable for folding sheep on the heavy soil on Agdell and when this was so the roots and tops were sliced and spread over the half plot. This comparison stopped for the 15th root crop in 1904, since when the crop was removed from the whole plot.

Lawes and Gilbert presented detailed yields and nutrient uptakes from this experiment only once (Lawes & Gilbert, 1894), though they used both yields and soil analyses to illustrate arguments, especially about nitrogen, in other papers. Warren (1958) described the experiment up to 1957 and gave more detailed soil analyses. The rotation experiment ended in 1951 because the manuring was no longer relevant to modern farming, and yields of swedes on plots 1 and 2 were affected by soil acidity caused by repeatedly giving ammonium salts.

Between 1951 and 1958 no further P and K were given; the plots were fallowed in 1952 and grew barley without N in 1953. From analyses of soil samples taken in spring 1953, a soil pH map was prepared and a liming scheme suggested to neutralise acidity on plots 1 and 2 and the southern halves of plots 3 and 4. More chalk was applied in 1959 and 1967. The amounts (cwt/acre) applied to plots 1, 2, 3 and 4 were:

Plot	1	2	3	4
Year	All	All	South half	South half
1954	60	80	10	10 to 30
1959	36	36	0	0
1967	46	46	46	46

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Between 1954 and 1957 the crops grown were barley in 1954 and spring wheat in 1955 both with basal N, beans without N in 1956 and potatoes with basal N in 1957. Cereal yields were small; Warren (1958) gave the yields of beans and potatoes. Fig. 1 shows that the P and K contents of the beans and potatoes were closely correlated with the amounts of soluble P and K in the 0–6 in. depth of soil in 1953, especially the P contents of the crops and soil analysis for P. So we decided to investigate the value of the residues from past fertiliser dressings in greater detail. This was done for potatoes, sugar beet and barley, grown in rotation with and without dressings of new P from 1959 to 1962, with results discussed by Johnston, Warren and Penny (1970). In addition to finding what effect the P residues had on arable crops, we also wanted to know for how long and at what rates P and K would be released from the residues. To do this half of each rotation plot was sown to grass in 1958, because grass given N could be expected to remove large amounts of P and K. To tell when the grass had exhausted the residues, the amounts of P and K remaining in the soil from the dressings given in the rotation experiment had to be estimated.

The amounts of residues of P and K

Two methods were used to estimate the amounts of residues: (1) from the balance between known additions as fertiliser and removals in crops grown; (2) from soil analysis. In neither method was it possible to allow for differences between the 'fed-on' and 'carted off' roots from 1848 to 1904. Probably crops following 'fed-on' roots removed more nutrients than after 'carted' roots, so mean composition and total removal has been used. Any effect on soil analysis was allowed for by sampling and analysing the soils of quarter plots and using a mean result.

A balance sheet for P and K. Warren (1958) estimated the P and K accumulating on plots given fertilisers but considered only the first 18 courses up to 1919, when yields were good. Yields of some crops later decreased, so removed less P and K, and we have prepared a new balance sheet. To do this, the rotation experiment was divided into six periods to allow for changes in manuring and the onset of acidity on plots 1 and 2. We then calculated from existing, but unpublished, records of total yield the mean annual total dry matter produced, using the % dry matter results that existed from crops grown before 1920 and means of these for other periods. Lawes and Gilbert (1894) gave amounts of P and K removed by the crops grown in courses 2–9 (1852–83) and from these we calculated the % P and % K in the crops of that period. We found that these P and K concentrations in the various crops agreed well with results obtained recently for crops grown similarly. So Lawes and Gilbert's results were used to calculate the P and K removed by the crops grown during all periods, except that a small allowance was made for extra K removed in crops grown on plots 3 and 4 which were given K after 1884. Appendix Tables 1, 2 and 3 give details of dry matter yields and P and K uptakes and Table 1 summarises the P and K additions and removals during the rotation experiment 1848 to 1951, and the years 1952–57.

Amounts of residues estimated by soil analysis. The soils were sampled at 0–9, 9–12 and 12–18 in. depth by quarter plots during spring 1958, and analysed for total and bicarbonate soluble-P and exchangeable-K. No attempt was made to determine total K because soils at Rothamsted differ so much in clay content that residues of K fertilisers cannot be assessed from the difference between total K of soils with and without residues. Table 2 gives the results; it also shows the total P, both for whole plots and the half

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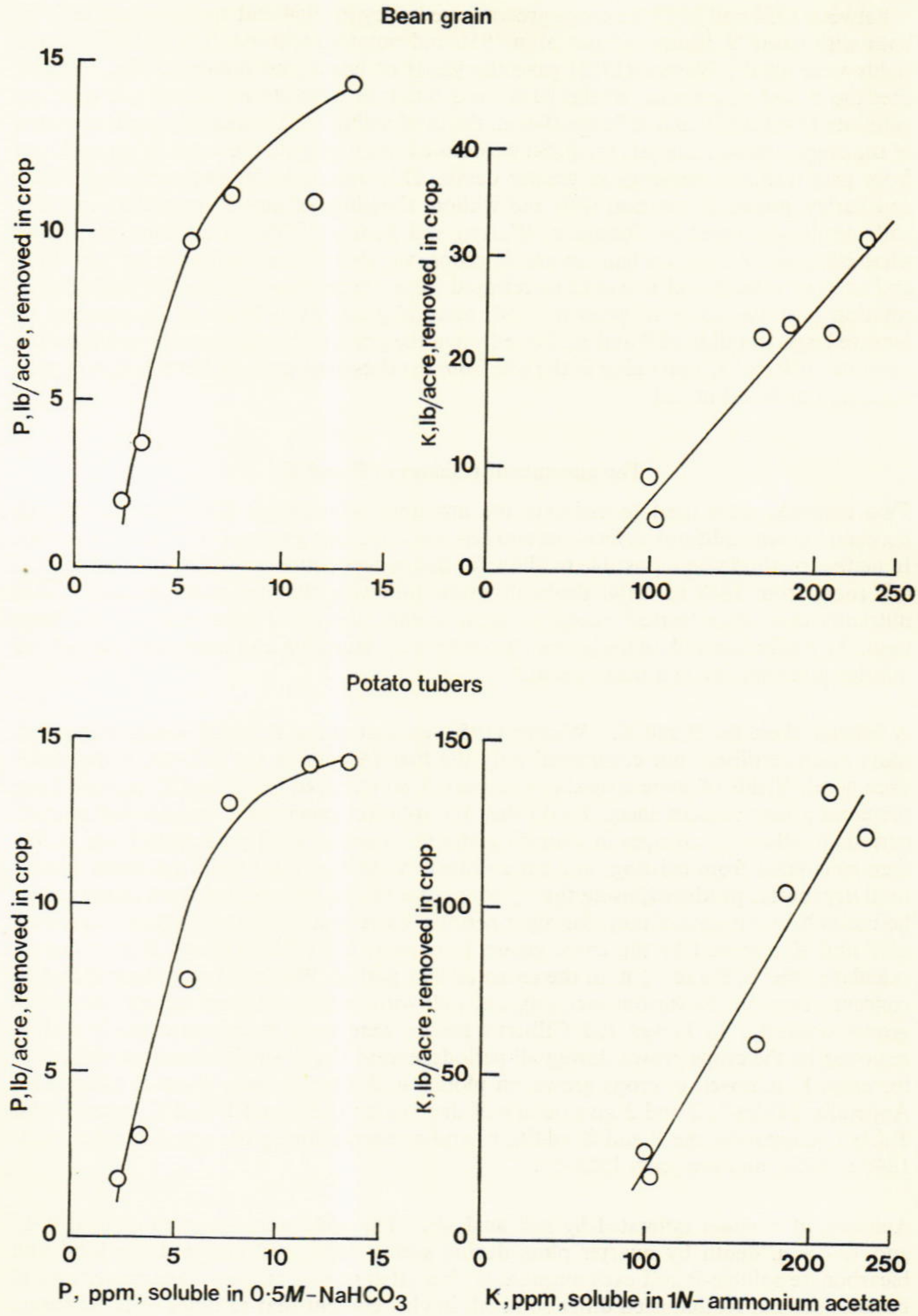

FIG. 1. Relationship between P and K content of beans and potatoes and readily soluble-P and -K in the soil of Agdell Field, Rothamsted, 1956–57.

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TABLE 1

Estimates of the P and K additions and removals and the mean annual changes in these nutrients in the Agdell experiment, 1848–1957

Plot	Treatment and rotation	Additions: As fertiliser	Additions: In rape cake	Additions: Total	Removals: 1848–1951	Removals: 1952–1957	Removals: Total	Additions minus removals	Mean annual change: 1848–1951 104 years	Mean annual change: 1848–1957 110 years
						P (lb/acre)				
1	NPK—fallow	890	490	1380	646	34	680	+700	+7·0	+6·4
2	NPK—clover	890	490	1380	778	38	816	+564	+5·8	+5·1
3	PK—fallow	890	0	890	455	46	501	+389	+4·2	+3·5
4	PK—clover	890	0	890	662	34	696	+194	+2·2	+1·8
5	None—fallow	0	0	0	276	14	290	−290	−2·6	−2·6
6	None—clover	0	0	0	307	11	318	−318	−3·0	−2·9
						K (lb/acre)				
1	NPK—fallow	4160	490	4650	3156	205	3361	+1289	+14·4	+11·7
2	NPK—clover	4160	490	4650	3750	197	3947	+703	+8·6	+6·4
3	PK—fallow	3280	0	3280	1640	234	1874	+1406	+15·8	+12·8
4	PK—clover	3280	0	3280	2586	163	2749	+531	+6·7	+4·8
5	None—fallow	0	0	0	1002	68	1070	−1070	−9·6	−9·7
6	None—clover	0	0	0	1239	58	1297	−1297	−11·9	−11·8

TABLE 2

Composition of the soils of the Agdell experiment, 1958

(Mean of quarter plot samples)

	Plot and depth in inches																	
	1			2			3			4			5			6		
	0–9	9–12	12–18	0–9	9–12	12–18	0–9	9–12	12–18	0–9	9–12	12–18	0–9	9–12	12–18	0–9	9–12	12–18
P soluble in $0{\cdot}5M$–$NaHCO_3$																		
ppm	20	11	4	14	7	3	17	7	3	6	3	2	3	1	1	2	1	1
Total P in whole plots																		
ppm	711	642	451	716	598	453	674	534	423	616	507	430	527	458	440	522	444	414
lb/acre	1669	524	736	1681	488	739	1582	436	690	1446	414	702	1237	374	718	1226	362	676
Total P in grass half plots																		
ppm	730	649	461	703	605	452	646	528	417	611	516	436	523	445	422	528	453	415
lb/acre	1714	530	752	1651	494	738	1517	431	680	1435	421	712	1228	363	689	1240	370	677
K soluble in $1N$ ammonium acetate																		
ppm	170	169	148	156	140	124	185	154	140	152	122	123	104	103	112	109	102	106
lb/acre	399	138	242	366	114	202	434	126	228	357	100	201	244	84	183	256	83	173

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plots where grass was later grown, and exchangeable K in lb/acre for the 0–18 in. depth of soil. We used 2 348 000 and 2 448 000 lb/acre as the weights of fine soil for the 0–9 in. and 9–18 in. depths respectively, as given by Hall (1905). These weights are less than those of the soils on Broadbalk because the Agdell soils contain more stones.

Soil analyses related to nutrient balances

Phosphorus. Fig. 2 shows a satisfactory agreement between the gains and losses of P between 1848 and 1958 and the total P in the 0–18 in. depth of soil. There are too few results to relate satisfactorily mean annual gains and losses with bicarbonate soluble-P,

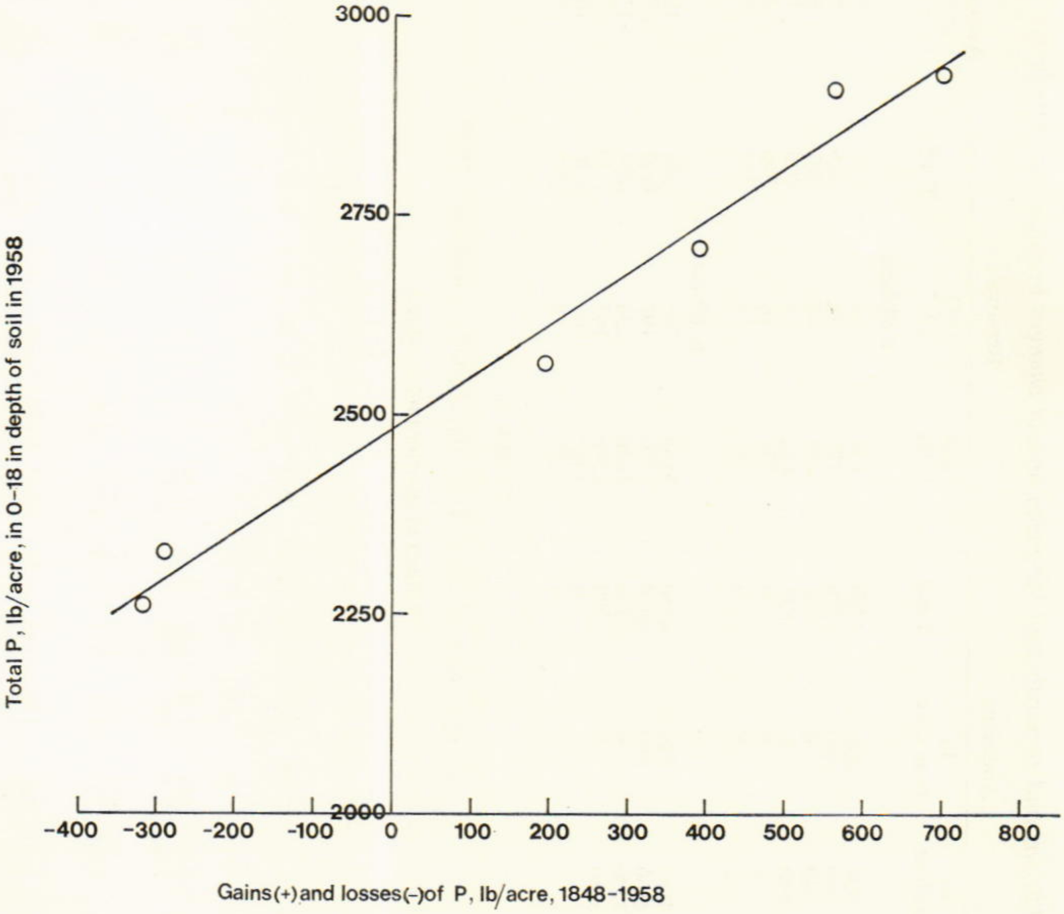

FIG. 2. Relationship between losses and gains of phosphorus (lb/acre) between 1848 and 1957 and the total P (lb/acre) in the 0–18 in. depth of soil in 1958 on Agdell Field, Rothamsted.

as Williams and Cooke (1971) did for the Rotation I soils at Saxmundham. However, their results and ours for Agdell can be combined. Fig. 3 shows that the relationship between annual gains and losses of P and bicarbonate soluble-P in the 0–9 in. depth of soil is linear, confirming Williams and Cooke's deduction. Fig. 3 also shows that, from these combined results, the soils will contain 9 ppm of sodium bicarbonate soluble-P when losses in crops are just balanced by additions of fertiliser-P, a value slightly less than the 10 ppm obtained from the Saxmundham results alone.

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Potassium. Fig. 4 shows a linear relationship between exchangeable K in the 0–9 in. depth of soil in 1958 and the calculated mean annual balance between additions of fertiliser-K and K removed in the crops between 1848 and 1957. Fig. 4 also compares similar results given by Williams and Cooke (1971) for the soils of Rotation I at Saxmundham and by Johnston (1969) for the Broadbalk soils at Rothamsted. With all three experiments there is a linear relationship but the slopes of the lines differ, and the

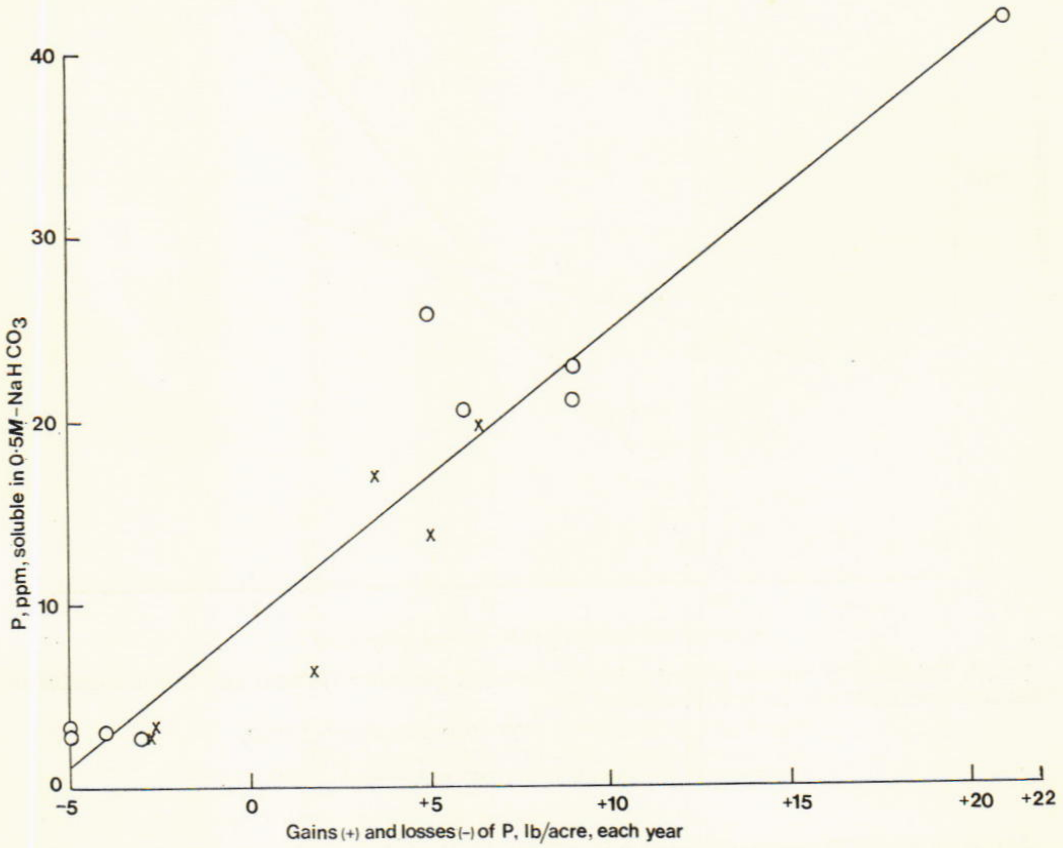

FIG. 3. Relationship between annual gains and losses of phosphorus (lb/acre) and P soluble in sodium bicarbonate solution in the 0–9 in. depth of soil.

○ Saxmundham Rotation I 1899–1969 soils sampled 1969.
× Rothamsted Agdell 1848–1957 soils sampled 1958.

Saxmundham soil differs from the other two more than they from each other. However, it seems that when K removed in crops is balanced by K added as fertiliser, all three of these old arable soils would contain around 150 ppm of exchangeable K.

The grass experiment, 1958–70

The six plots of the rotation experiment were divided into west and east halves in spring 1958 and grass was grown on one half of each plot from 1958 to 1970. The grass was given 0·8 cwt N/acre for each cut taken at silage stage.

The experiment can be divided into two periods:

(1) 1958 to 1963 when the grass measured the combined effects of P and K residues;

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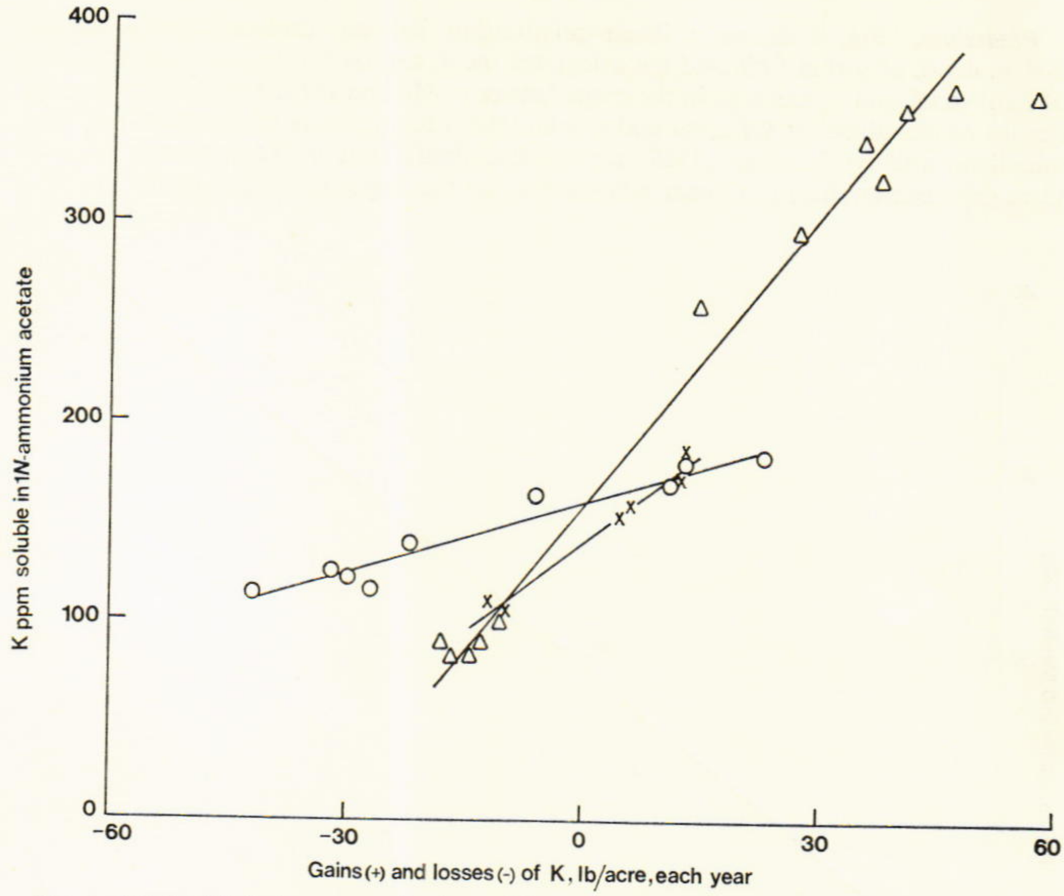

FIG. 4. Relationship between annual gains and losses of potassium (lb/acre) and K exchangeable to 1*N*-ammonium acetate in the 0–9 in. depth of soil.

○ Saxmundham Rotation I 1899–1969 soils sampled 1969.
× Rothamsted Agdell 1848–1957 soils sampled 1958.
△ Rothamsted Broadbalk 1844–1967 soils sampled 1966.

(2) 1964 to 1970 when the separate effects of P and K residues were measured by giving K and P, in addition to N, to sub-plots testing P and K respectively. Three amounts each of new P and K were also tested.

The first period, 1958–63

Italian ryegrass (S22) was grown in 1958–59, cocksfoot (S37) in 1960–63, and Table 3 show the yields of dry grass each year.

Italian ryegrass (S22), 1958–59. Sown in spring 1958 the ryegrass established well and two cuts were taken (late July, late October). Table 3 shows that, with each old manurial treatment, yields were much the same whether after the fallow or clover rotation. The starved soils produced a little more than 30 cwt/acre of dry grass, whereas the PK and NPK plots yielded 45 and 53 cwt/acre respectively. Table 1 shows that both NPK plots contain more P than the corresponding PK plots, whereas the NPK- and PK-fallow plots contain more K than the NPK- and PK-clover plots. The larger yields of grass on the NPK plots, irrespective of previous rotation, therefore support Warren's (1958)

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TABLE 3

Yields (cwt/acre) of dry grass on Agdell, Rothamsted, 1958–63

	Old treatments, 1848–1951					
	Rotation with fallow			Rotation with clover		
	None	PK	NPK	None	PK	NPK
			Italian ryegrass (S22)			
1958 (2 cuts)	34·1	45·9	53·8	31·4	43·6	52·4
1959 (3 cuts)	43·1	63·6	66·8	22·0	59·6	58·7
			Cocksfoot (S37)			
1960 (2 cuts)*	7·1	36·4	49·3	11·0	36·1	45·0
1961 (3 cuts)	37·7	62·8	71·3	33·6	62·6	59·6
1962 (3 cuts)	40·3	67·4	69·9	30·5	60·0	68·6
1963 (1 cut)	3·8	4·5	2·1	2·1	5·6	6·1
Mean annual yield, 1958–62	32·5	55·2	62·2	25·7	52·4	56·9
Effect of residues	—	22·7	29·7	—	26·7	31·2

* Two cuts from NPK plots, only one from other plots.

deduction, from the yields of beans and potatoes, that shortage of P rather than of K limited yield on the other plots.

In 1959 three cuts were taken, in late May, early July and late August. The unmanured-fallow plot yielded 43 cwt/acre of dry grass, but the unmanured clover plot only 22 cwt/acre. This difference must be because the unmanured-fallow plot still had more P and K than the unmanured-clover plot from which the legumes removed P and K during the rotation experiment. Yields were more than doubled by the residues but they were 4 and 8 cwt/acre smaller after clover than after fallow on the PK and NPK plots respectively. Thus, after growing grass for one year the larger PK residues on the fallow rotation plots were affecting yield. More than half the yield in 1959 came from the first cut and the third cut produced only 3–12 cwt/acre, so the ryegrass was ploughed in during November.

Cocksfoot (S37), 1960–63. Cocksfoot was sown in early April 1960 and dressed with N in May. The grass established well on the NPK plots but badly on the others and parts of them were resown late in June. On the NPK plots the grass was cut and weighed late in July, when on the others it was topped to encourage tillering, and all were top-dressed with N. All plots were cut late in September, so yields for 1960 (Table 3) are from two cuts on the NPK plots and one on the others. Yield on the starved soil was only 7 cwt/acre after the fallow and 11 cwt/acre after the clover rotation. The clover plot probably yielded more because the grass established better. Later, when once established, the grass yielded more on the unmanured-fallow plot which contained more P and K. Yields on the PK and NPK plots were 36 and 47 cwt/acre respectively.

In 1961 the cocksfoot was well established on all plots and the first cut was taken at mid-May, followed by cuts in July and September. Table 3 shows that the starved soils produced five times as much as in 1960 after the fallow rotation (38 cwt/acre) and three times as much (34 cwt) after the clover, but, even so, the residues in the PK plots increased yields to 63 cwt acre after both rotations. Yield was further increased to 71 cwt/acre by the residues on the NPK-fallow plot.

Table 3 also shows that total yields from three cuts in 1962 (early June, mid-August and early October) were much the same as in 1961. The unmanured-fallow plot yielded 10 cwt/acre more than the unmanured-clover plot and the residues increased yields to between 60 and 70 cwt/acre.

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The severe winter of 1962–63 killed much of the cocksfoot and after one cut, maximum yield was only 6 cwt/acre, the grass was destroyed with paraquat and the land was ploughed during the autumn.

Mean yields, 1958–62. Table 3 shows mean annual yields of dry grass for the years 1958–62. On the unmanured, PK and NPK plots after the fallow rotation yields were 6·8, 2·8 and 5·3 cwt/acre more each year respectively than after the clover rotation, because the fallow plots had lost less P and K during the rotation experiment 1848–1951. The mean annual gains from the PK residues were 22·7 and 26·7 cwt/acre on the PK-plots and 29·7 and 31·2 cwt/acre on the NPK-plots after fallow and clover respectively. Averaged over all treatments, the annual gain from the PK residues was 27·6 cwt/acre of dry grass, i.e. the PK residues doubled the yield obtained on unmanured plots. This result can be compared with the effects of the residues on beans (an extra 14·1 cwt/acre grain) in 1956 and on potatoes (an extra 9·5 tons/acre tubers) in 1957. The residues increased the yield of beans by three times and of potatoes by 3·5 times.

Nutrients removed, 1958–63. Table 4 shows the amounts of P and K removed by the grass between 1958 and 1963 and the extra uptake from the residues.

TABLE 4

Amounts of P and K removed each year by the grass grown on Agdell, Rothamsted, 1958–63

	Old treatments, 1848–1951					
	Rotation with fallow			Rotation with clover		
	None	PK	NPK	None	PK	NPK
			P removed, (lb/acre)			
Italian ryegrass						
1958	7·6	14·1	18·4	5·9	12·1	16·7
1959	6·4	13·1	15·1	3·5	11·5	12·1
Cocksfoot						
1960	1·2	10·4	14·6	1·6	8·5	12·1
1961	5·2	14·2	16·2	4·8	11·4	13·2
1962	5·9	14·5	16·5	4·4	10·8	14·9
1963	0·6	1·2	0·6	0·3	1·2	1·5
P removed annually 1958–63	4·5	11·2	13·6	3·4	9·2	11·8
Total P removed	26·9	67·5	81·4	20·5	55·5	70·5
Extra P from residues	—	40·6	54·5	—	35·0	50·0
			K removed, (lb/acre)			
Italian ryegrass						
1958	115	152	187	111	171	193
1959	90	170	189	45	149	153
Cocksfoot						
1960	18	125	171	29	104	108
1961	61	162	184	54	118	105
1962	44	114	131	34	74	83
1963	4	7	3	2	7	5
K removed annually 1958–63	55	122	144	46	104	108
Total K removed	332	730	865	275	623	647
Extra K from residues	—	398	533	—	348	372

Phosphorus. From plots not given P since 1848, the grass removed 4·5 lb P/acre each year after the fallow and 3·4 lb P after the clover rotation. The extra amounts of P removed each year from the residues ranged from 5·8–9·1 lb P/acre. The extra P taken

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up from the residues during the six years 1958–63 can be related to the estimates (in Table 1) of the P accumulated in the soil during the rotation experiment (1848–1951):

	Plot			
	PK fallow	NPK fallow	PK clover	NPK clover
Extra P removed by the grass in six years from Table 4 (lb/acre)	40·6	54·5	35·0	50·0
Balance sheet estimate of extra P accumulated during the rotation experiment from Table 1 (lb/acre)	389	700	194	564
% recovery of residues in six years by grass	10	8	18	9
Years to recover total residue (assuming present rate continued)	57	77	33	68

Only 8–18% of the total P residues were recovered during the six years; the smaller percentage recoveries were on the plots with most residues, suggesting that there was little luxury uptake. At this rate of recovery a total of between 33 and 77 years would be needed to recover all the residues.

Table 5 shows that each year the grass removed similar amounts of P from plots with different P contents as did crops of beans and potatoes.

TABLE 5

Comparison of the amount of P and K removed each year by beans, potatoes and grass on Agdell, 1956–63

	Old treatments, 1848–1951					
	Rotation with fallow			Rotation with clover		
	None	PK	NPK	None	PK	NPK
	P removed (lb/acre)					
Beans, 1956	3·8	14·4	10·9	2·0	9·8	11·1
Potatoes, 1957	3·2	14·3	14·2	1·8	7·7	13·0
Grass, mean 1958–63	4·5	11·2	13·6	3·4	9·2	11·8
	K removed (lb/acre)					
Beans, 1956	9	32	23	5	23	23
Potatoes, 1957	27	121	135	20	60	105
Grass, mean 1958–63	55	122	144	46	104	108

Potassium. Table 4 shows that, on average, grass removed 55 and 46 lb K/acre from the unmanured soil after the fallow and clover rotations. However, these are averages of a wide range of values. After the period of comparatively unexhaustive cropping between 1952 and 1957, the Italian ryegrass removed 111–115 lb K from these soils in 1958, but the equally large crops of cocksfoot in 1961 and 1962 removed only between 34 and 61 lb K/acre. From 1958 to 1963, between 60 and 90 lb of extra K/acre were removed on average each year from the plots with residues. The total extra K taken up from the residues during the six years can be related to the estimates (in Table 1) of the K accumulated in the soil during the rotation experiment:

	Plot			
	PK fallow	NPK fallow	PK clover	NPK clover
Extra K removed by the grass in six years from Table 4 (lb/acre)	398	533	348	372
Balance sheet estimate of extra K accumulated during the rotation experiment from Table 1 (lb/acre)	1406	1289	531	703
% recovery of residues in six years by grass	28	41	66	53

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Much more (28–66%) of the estimated K residues were recovered than of the P residues and it seemed that only another five or so years would be needed to recover all the residues on some plots.

Table 5 shows that, in contrast to P, the grass extracted much more K from the unmanured soils than did the beans or potatoes, but that the potatoes removed much the same amount from soils with residues, except from the PK-clover plot.

The second period, 1964–70

After the cocksfoot was killed in 1963 the plots were ploughed and sown with timothy (S51) in 1964. Each grass half-plot was divided into eight sub-plots to test four amounts each of new P and K with basal dressings of K and P respectively.

Treatments and symbols were:

Nutrients as P_2O_5 and K_2O (cwt/acre) given as triple superphosphate and potassium chloride

P test sub-plots	P_2O_5	K_2O	K test sub-plots	P_2O_5	K_2O
P_0K_4	none	10	P_4K_0	16	0
P_1K_4	4	10	P_4K_1	16	2·5
P_2K_4	8	10	P_4K_2	16	5·0
P_4K_4	16	10	P_4K_4	16	10·0

Thus from 1964 to 1970 the effects of the residues of P and K were measured separately. Appendix Tables 4 and 5 show yields of dry grass each year. To maintain the differences in soil P and K between the sub-plots, the P and K removed in the grass was returned as an equivalent amount of fertiliser P and K, except that sub-plots testing P_0K_4 were not given P and those testing P_4K_0 were not given K. Also, in 1964 the arable half-plots were similarly divided into eight sub-plots, which were given the same combinations of P and K fertilisers. Between 1964 and 1969 these sub-plots were fallowed and received no additional fertiliser.

Timothy (S51), 1964–67. The Timothy was sown early in May 1964. Large benefits from all amounts of new P (up to 16 cwt P_2O_5/acre) and new K (up to 10 cwt K_2O/acre) showed soon after the grass emerged, but dry weather after June curtailed growth and the grass was cut only once, late in August. The timothy established so badly and grew so slowly without new P (P_0K_4 treatments) that yields could not be measured on plots without residues and were small with. More important, was that even with the largest amounts of new fertiliser given (16 cwt P_2O_5/acre), yields were twice as much on the old NPK-plots as on the starved soils:

New fertiliser, 1964 (cwt/acre)		Old treatments, 1848–1951 Mean of fallow and clover rotations		
P_2O_5	K_2O	None	PK	NPK
		Dry grass (cwt/acre) 1964		
0	10	0	1·0	5·2
16	10	8·4	11·0	18·8

Thus newly-sown grass responded, both to the residues and the new dressings of P, much as the arable crops did in 1959–62.

Giving new K had irregular effects but the smallest amount usually doubled yield and there was no benefit from giving more.

By 1965 the timothy was well established and three cuts were taken, at mid-May, late June and early October. Plots, which in the previous year yielded 0–7 cwt dry grass/acre,

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now yielded 57–108 cwt/acre. On the P test sub-plots after the fallow rotation, yields without new P were 83, 86 and 108 cwt/acre on the unmanured, PK and NPK plots respectively. New P was most effective on the old unmanured and PK plots, increasing yield by 16–18 cwt/acre, but even so yields were less than the 117 cwt on the NPK plot. After the clover rotation, yields without new P were 57, 84 and 92 cwt/acre on the unmanured, PK and NPK plots respectively. Yields on all the clover rotation plots were increased by new P and were as large on the unmanured plot as on the PK and NPK plots. For all tests, there was little or no benefit from more than the smallest dressing of new P (4 cwt P_2O_5/acre). Appendix Table 4 also shows that, on the K test sub-plots in 1965, the grass yielded 89 cwt/acre on the unmanured-fallow plot without new K and still more (97 cwt) with residues of K on the NPK plot. On the clover rotation plots there was little benefit from residues. Given new N and P, but not K, the unmanured-clover plot yielded 90 cwt/acre even after cropping for 117 years without K manuring. New K increased yield little on the starved soils but gave moderate increases in the presence of K residues. Hence, with new K, yields were 10–13 cwt/acre more on plots with old K residues than on those without. The smallest amount of new K was usually enough.

In 1966 the grass was cut four times, at mid-May, late June, mid-August and mid-October. Total March to September rainfall was much the same in both years, 19·0 in. in 1965 and 17·6 in 1966, but on the impoverished soils, yields (cwt/acre) were much less in 1966 than in 1965:

	Unmanured-fallow plots		Unmanured-clover plots	
	1965	1966	1965	1966
Without fresh P	83·1	43·2	56·6	29·0
Without fresh K	88·8	59·4	90·4	55·8

This suggests that, on these impoverished soils, the P and K released by weathering and not used by the very small crops in 1964 remained to supply the crop grown in 1965; however, weathering was too slow to maintain in 1966 the large yields in 1965. In 1966 the much smaller yields on the starved soils made the single and combined effects of residues and new P and K seem much larger than in 1965, but Appendix Table 4 shows that maximum yields with residues and new dressings of both P and K were similar to those in 1965.

By 1967 the timothy was badly infested with couch grass and was cut only once, early in June. The couch made yields irregular but they followed the pattern of the previous two years (Appendix Table 4). The land was ploughed and then rotary cultivated four times during July and August to kill the couch. Timothy was sown again in early September.

Timothy (S51), 1968–70. By spring 1968 the timothy was well established except where new P was not applied in 1964 (P_0K_4 sub-plots); however, of these sub-plots, growth was least bad on the NPK-fallow plot, which consistently yielded the most between 1964 and 1967. Timothy was resown on the P_0K_4 sub-plots on the starved soils in mid-April. The grass was not cut on these sub-plots, or on the P_0K_4 sub-plot of the PK-clover rotation, at the first cut in May. Second and third cuts were taken in July and October and by October yields on all P_0K_4 plots were much the same. Total yields (Appendix Table 5) from the three cuts were increased by P residues on the NPK plots from 23–65 cwt/acre after the fallow rotation and from 26–46 cwt/acre after clover. Though residues on fallow rotation plots were again more effective than on clover rotation plots, maximum yield was the same (87–88 cwt/acre) after both rotations when new P was given. New P was less effective on the starved soils, increasing yields to only 73 cwt/acre. Both old and new K had much smaller effects than old and new P, because on the starved

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soils yields on the P_4K_0 sub-plots were much larger than on the P_0K_4 sub-plots. This confirmed previous deductions that shortage of P rather than of K limited yield on this soil. Appendix Table 5 shows that K residues on the PK plots increased yields from 56 to 67 cwt/acre after the fallow rotation and from 65 to 72 cwt/acre after the clover rotation. In 1968 the K residues on the NPK plots were less effective than those on the PK plots. After the fallow rotation this was probably just chance, because in 1969 yields on the P_4K_0 sub-plots were, as usual, better after NPK-fallow than after PK-fallow. After the clover rotation, yields on the P_4K_0 sub-plots were smaller on the NPK plot than on the PK plot from 1966, by as much as 20 cwt/acre in 1968 and 1969. Possibly this is related to release of soil-K because the soil of the NPK-clover plot contains less clay. However, yields were the same on both plots when new K was given.

In 1969 the grass was again cut three times, in early June, early August and mid-October. Yields (in Appendix Table 5) were much the same as in 1968 except that sub-plots without new P yielded rather better.

The plots testing new P were ploughed during autumn 1969 to measure with arable crops the effects of the P residues built up in these soils under grass and fallow. The sub-plots testing K remained in grass in 1970. Only two cuts were taken, in June and August, before this grass also was ploughed because it had again become infested with couch. The yields are in Appendix Table 5.

Mean yields, 1964–69. Table 6 shows the mean annual yields, from 1964 to 1969, given by each combination of P residues and new P and of K residues and new K when the P and K removed in each crop were returned as equivalent amounts of fertiliser, except that the P_0K_4 sub-plots got no P and the P_4K_0 sub-plots no K. Only one cut was taken in two of the six years so maximum mean yields were only a little larger than 70 cwt dry grass/acre. Giving basal dressings of P and K to sub-plots testing K_0 and P_0 respectively,

TABLE 6

Mean annual yields of dry grass (cwt/acre) from combinations of residues of old P with new P and from combinations of residues of old K with new K, 1964–69

New treatments in 1964		Old treatments, 1848–1951					
		Rotation with fallow			Rotation with clover		
P	K	None	PK	NPK	None	PK	NPK
0	4	33·3	48·6	64·1	24·6	40·6	52·9
1	4	62·2	66·8	71·4	62·8	65·9	69·1
2	4	65·4	65·8	71·8	66·1	59·8	71·8
4	4	65·6	68·1	72·8	65·6	67·8	70·1
4	0	50·6	52·5	57·3	46·5	59·8	48·1
4	1	65·6	64·7	69·2	65·4	69·4	69·8
4	2	63·6	63·4	69·5	64·3	65·5	70·3
4	4	67·6	64·3	73·1	65·8	68·1	73·1

P_0 = no P_2O_5 P_1 = 4 cwt P_2O_5/acre P_2 = 8 cwt P_2O_5/acre P_4 = 16 cwt P_2O_5/acre
K_0 = no K_2O K_1 = $2\frac{1}{2}$ cwt K_2O/acre K_2 = 5 cwt K_2O/acre K_4 10 cwt K_2O/acre

showed that yields were restricted much more by shortage of P than of K residues. Residues of P in the PK plots increased yield by 15 cwt/acre and in the NPK plots by 30 cwt/acre. Compared with the first period when combined PK effects were measured, the P residues in the PK plots increased yield less during the second period but the yield was increased by the same amount during both periods on the NPK plots. By contrast, K residues increased yield by only 2 and 7 cwt/acre on the PK- and NPK-fallow plots

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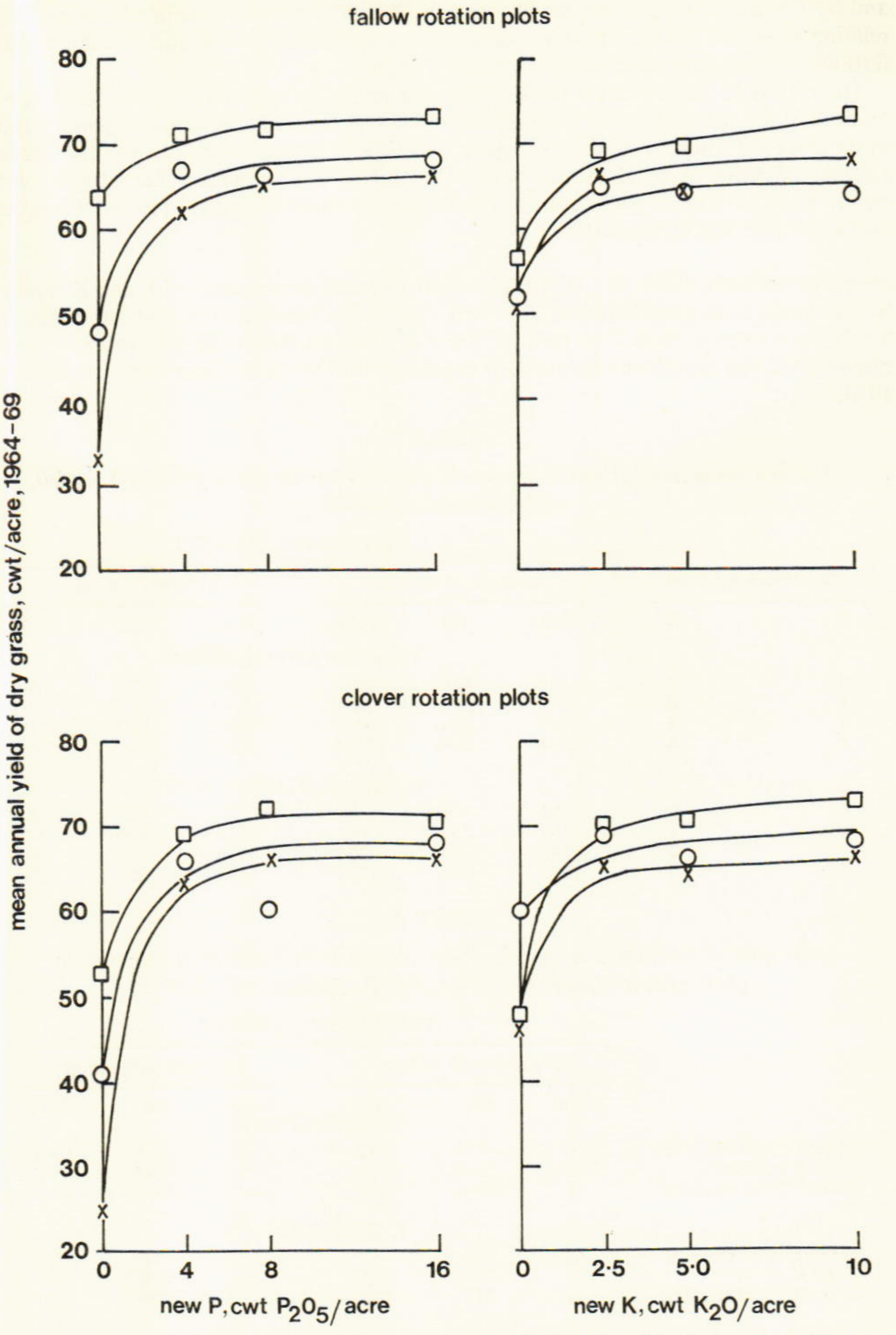

FIG. 5. Relationship between yield of dry grass (cwt/acre) 1964–69 and fresh dressings of P and K on the Agdell rotation experiment plots which were, unmanured, ×; or given PK, ○; or given NPK, □, from 1848 to 1951.

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and by 13 and 2 cwt/acre on the PK- and NPK-clover plots. These increases bear little relation to those during the first period and suggest that soil-K rather than residual fertiliser-K was more effective in controlling yield.

The results in Table 6 were used to plot the response by grass to new P and new K on each of the old plots, after both fallow and clover (Fig. 5). The grass responded much more to new P than to new K but there was little response to more than the smallest amount of either P or K tested, both with and without residues. The shapes of the curves show no loss of yield even at the largest amounts of both P (16 cwt P_2O_5/acre) and K (10 cwt K_2O/acre) tested.

Nutrients removed, 1964–70. Appendix Table 6 shows the amounts of P and K removed by the grass each year between 1964 and 1970 from the P and K test sub-plots, and Table 7 the average annual removal of P and K. Table 8 shows the amounts of P and K removed on the sub-plots without new dressings of P or K fertiliser between 1964 and 1970.

TABLE 7

Average amounts of P and K removed each year by the grass grown on Agdell, Rothamsted, 1964–70

New treatment 1964		Old treatments, 1848–1951					
		Rotation with fallow			Rotation with clover		
P	K	None	PK	NPK	None	PK	NPK
		P removed (lb/acre), 1964–69					
0	4	5·6	9·9	15·2	3·2	7·1	10·1
1	4	16·4	21·9	24·5	17·3	18·1	20·6
2	4	19·0	22·0	26·0	19·8	18·9	23·4
4	4	21·4	26·0	27·6	22·2	22·5	24·0
		K removed (lb/acre), 1964–70					
4	0	62	78	88	57	90	63
4	1	164	182	185	176	186	176
4	2	181	184	204	174	192	208
4	4	210	206	228	197	221	229

TABLE 8

Amounts of P removed by grass grown without new P and of K removed by grass grown without new K on Agdell, Rothamsted, 1964–70

	Old treatments, 1848–1951					
	Rotation with fallow			Rotation with clover		
	None	PK	NPK	None	PK	NPK
	P (lb/acre), 1964–69					
Mean annual removal	5·6	9·9	15·2	3·2	7·1	10·1
Total P removed	33·8	59·4	91·1	19·2	42·5	60·4
Extra P from residues	—	25·6	57·3	—	23·3	41·2
	K (lb/acre), 1964–70					
Mean annual removal	62	78	88	57	90	63
Total K removed	433	546	615	400	630	440
Extra K from residues	—	113	182	—	230	40

Phosphorus. Table 7 shows that the grass removed 5·6 lb P/acre from the unmanured plots after fallow and 3·2 lb P/acre after clover: much the same amounts, 4·5 and 3·4 lb

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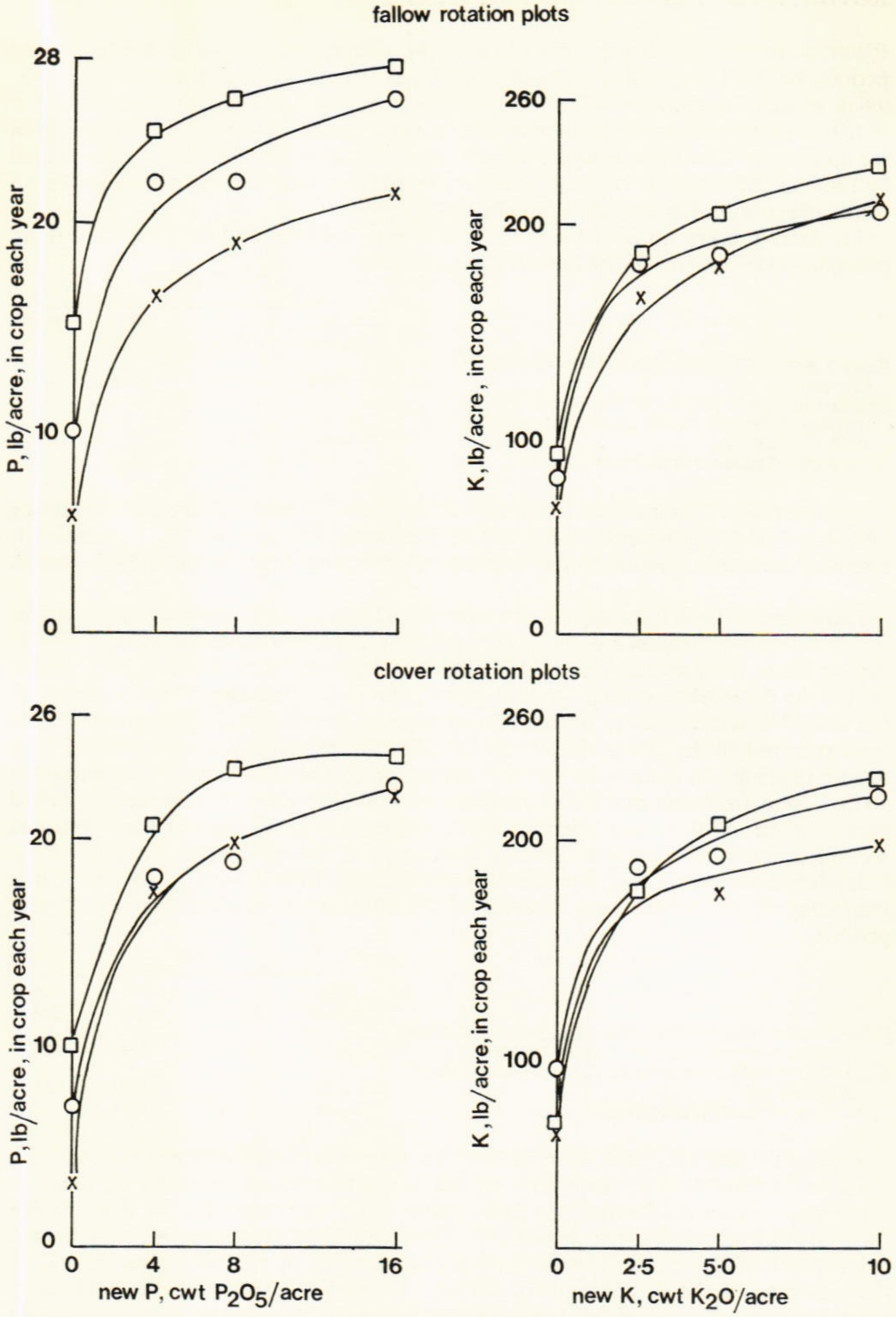

FIG. 6. Relationship between the mean amounts of P (lb/acre, 1964–69) and of K (lb/acre, 1964–70) removed in the crop each year and fresh dressings of P and K on the Agdell rotation experiment plots which were, unmanured, ×; or given PK, ○; or given NPK, □ from 1848 to 1951.

P/acre, were removed during 1958–63 (Table 4). During the second, as during the first period, the extra amounts of P removed each year from the residues ranged from 3·9–9·6 lb P/acre. An extra 9–14 lb P/acre was removed from the first dressing of new P tested; the amount was almost independent of the P present in the soil as residues. With the largest amount of new P some, but not all, of the differences between uptake caused by residues had disappeared; most P was removed from soils with most residues. Fig. 6 shows the relationship between P uptake and P applied.

The extra P taken up from the residues between 1964 and 1969 can be related to an estimate of the amount of residues remaining in 1964:

	Plot			
	PK fallow	NPK fallow	PK clover	NPK clover
Extra P removed by grass during 1964–69 (Table 8) (lb/acre)	25·6	57·3	23·3	41·2
Estimate of extra P in 1964 (lb/acre) [extra P from rotation experiment (Table 1) minus P removed 1958–63 (Table 4)]	348	646	159	514
% recovery of residues in six years by grass	7	9	14	8

The proportion of the residues recovered during 1964–69 was much the same as during 1958–63, so the P remained as available as previously. The recovery of the residues is discussed further in relation to the estimates of their amount from soil analysis results.

Potassium. Table 7 shows that, on average, 62 and 57 lb K/acre were removed by the grass from the unmanured plots after the fallow and clover rotations during 1964–70, slightly more than during 1958–63. Though shortage of P may have slightly limited growth on these plots during the first period, the close similarity of the K removals (62 and 57 lb K/acre second period, 55 and 46 lb K/acre first period) suggests that the grass removed all the K it could get and that, on average, this soil releases around 55 lb K/acre annually. In contrast to the first period, when the grass removed an extra 60–90 lb K/acre from the plots with residues, only 6–33 lb extra K/acre were removed each year during the second period. Also, whereas the percentage of the P residues recovered was much the same during both periods, the percentage recovery of the estimated K residues during the second period ranged from 11–125%. However, it is interesting to look at the total recovery of the estimated K residues over the 12-year period:

	Plot			
	PK fallow	NPK fallow	PK clover	NPK clover
Balance sheet estimate of the extra K accumulated during the rotation experiment from Table 1 (lb/acre)	1406	1289	531	703
Extra K removed by the grass in 12 years from Tables 4 and 8 (lb/acre)	511	715	578	412
% recovery of the residues by grass	36	55	109	59

The larger the amount of the estimated residue, the smaller was the percentage recovery. It seems improbable that much more of the K residues would be recovered were the experiment continued, because the grass removed so very much less of them during 1964–70 than previously. The amount of K removed from these sub-plots was limited only by lack of K because twice as much K was removed on sub-plots given new K. If the estimates of the K accumulated during the rotation experiment are reasonably correct, the fate of some of this K requires explaining. It may simply have been leached so far down into the soil that the grass roots failed to reach it. Alternatively, as the release and fixation of K in soils are reversible reactions, it may have become fixed so that its

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release is now no faster than that of 'native' soil-K. Whatever the explanation, it seems that 40–60% of the larger K residues are not available even to such an exhausting crop as grass.

Table 7 shows that with new K, the grass removed much more. From the smallest dressing of new K (2·5 cwt K_2O/acre), it removed 100 lb K/acre after each old treatment. From the other two amounts (5·0 and 10 cwt K_2O/acre), it removed only a further 20–40 lb K/acre each year. Fig. 6 shows the relationships between K uptake and K applied.

The relationship between yield and soil analysis

Phosphorus. Fig. 7a and b shows that both the total mean annual yield of dry grass from 1958–63 (Fig. 7a) and the mean annual uptake of P by the grass (Fig. 7b) are correlated with the amount of readily soluble P in the soil of the plots in 1958 measured by extraction with 0·5*M*–$NaHCO_3$. Fig. 7c and d shows that the average yield of dry grass and the P removed during the years 1968 and 1969 were similarly correlated with the readily soluble P in the soil in 1969. During the first period, but not in the second, the response curve became much flatter after about 10 ppm bicarbonate soluble-P. In the range 8–10 ppm bicarbonate soluble-P each 1 ppm increase gave an extra 0·8 and 2·5 cwt dry grass/acre in the two periods respectively. The much smaller value during the first period (1958–63) on Agdell may be because the mean yields included two very poor yields in 1960 and 1963. Mattingly *et al.* (1971) have reported that for Italian ryegrass in 1966–68, on Sawyers II and Delharding fields at Rothamsted, they obtained an extra 3·2 and 5·1 cwt dry grass/acre respectively for each 1 ppm increase in bicarbonate soluble-P at a mean soil value of 8–9 ppm.

Table 9 shows the changes in the bicarbonate soluble-P between 1958 and 1969. Although between 40 and 60 lb P/acre were removed from the unmanured plots of the clover and fallow rotations there was very little change in soluble-P content of the soils

TABLE 9

Amounts of soluble-P in the soils of the Agdell grass experiment, 1958–69

Plot	Treatment 1848–1951	P, ppm, soluble in 0·5*M*–$NaHCO_3$. Soils 0–9 in. deep not given new P in 1964: 1958	1961	1967	1969
1	NPK—fallow	20·8	13·6	11·4	11·8
2	NPK—clover	13·0	8·2	6·8	8·0
3	PK—fallow	15·6	9·0	7·7	5·6
4	PK—clover	6·0	4·6	4·4	4·0
5	None—fallow	3·0	2·5	4·4	4·0
6	None—clover	2·4	1·9	3·9	4·5

between 1958 and 1969, the bicarbonate soluble-P tending to increase slightly. On the other four plots, which had residues of P, the bicarbonate soluble-P decreased as the extra P from the residues was removed. With one exception, the decrease in bicarbonate soluble-P was related to, but did not account for all, the extra P removed. The exception was plot 3 (PK-fallow), which had anomalously much soluble P in 1958; by 1969, however, the soluble-P remaining was well related to the estimate of the total P residues.

Table 10 shows that the extra P taken up from the residues was not only well related to the estimate of the P remaining in the soil from the balance sheet shown in Table 1, but also to the estimate of the amount of the residues from the analyses for total P in the 0–18 in. depth of soil shown in Table 2. During the years 1958–69 the grass recovered on average 20 and 18% of the P residues estimated by the two methods. The only discordant result is the apparently better than average recovery of P on the PK-clover plot, when the

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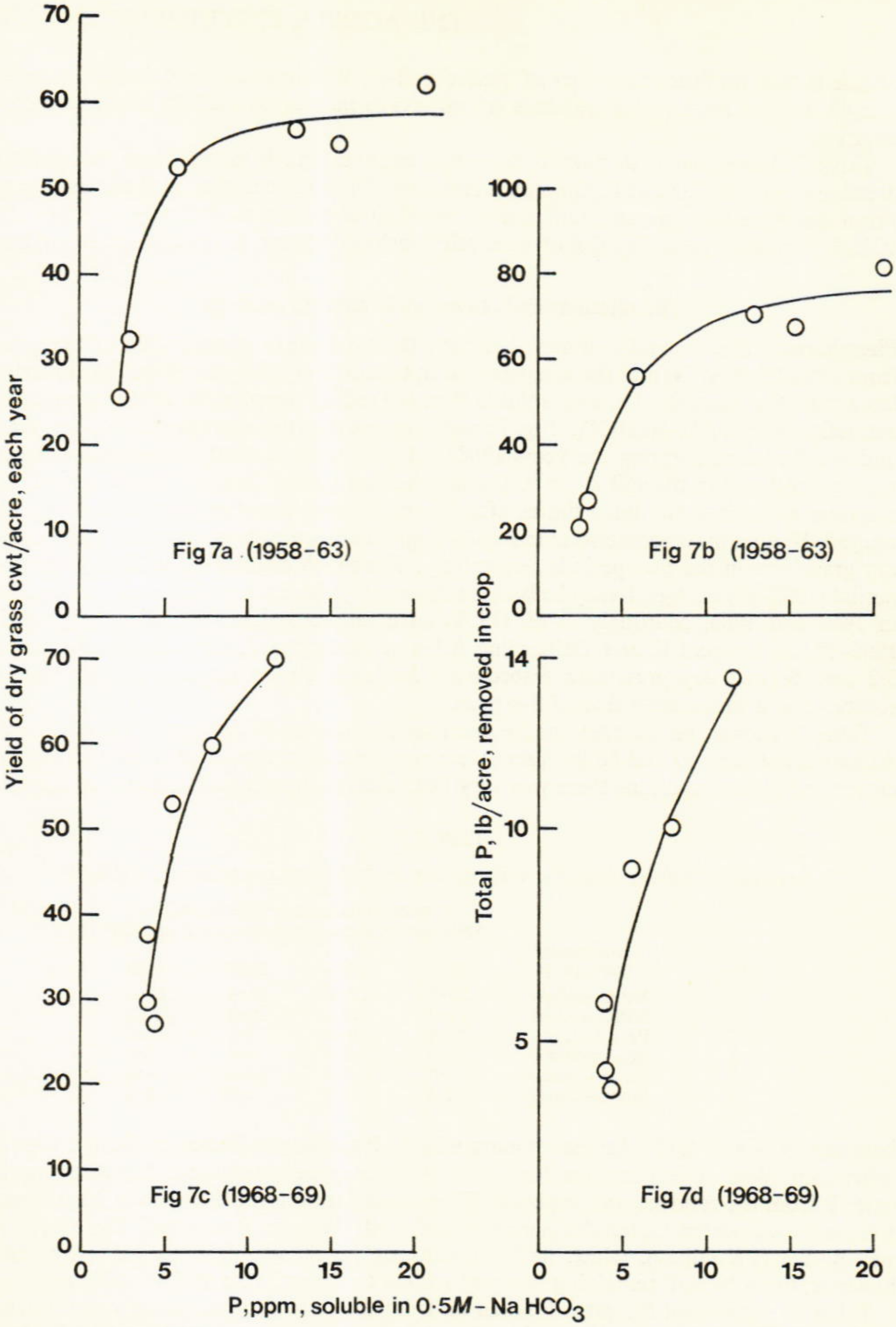

FIG. 7. Relationship between both yield of dry grass (cwt/acre) and P (lb/acre) removed in the grass and sodium bicarbonate soluble-P in the 0–9 in. depth of soil on Agdell Field, Rothamsted.

(a) Mean annual yield 1958–63 and soluble-P in soil in 1958.
(b) Total P removed 1958–63 and soluble-P in soil in 1958.
(c) Mean annual yield 1968–69 and soluble-P in soil in 1969.
(d) Total P removed 1968–69 and soluble-P in soil in 1969.

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TABLE 10

Relationship between the P removed by grass between 1958 and 1969 and the estimates of the total P residues in the soils of the Agdell grass experiment in 1958

	Old treatments, 1848–1951					
	Rotation with fallow			Rotation with clover		
	None	PK	NPK	None	PK	NPK
Total P removed by grass 1958–69 (lb/acre)	60·7	126·9	172·5	39·7	98·0	130·9
Extra P from the residues	—	66·2	111·8	—	58·3	91·2
Estimates of extra P in the soil (lb/acre)						
(a) from the balance sheet (Table 1)	—	389	700	—	194	564
% recovery	—	17	16	—	30	16
(b) from the analyses for total P in the soil (0–18 in. deep) of the grass plots (Table 2)	—	349	716	—	280	595
% recovery	—	19	16	—	21	15

balance sheet estimate for the P remaining in the soil is used. Probably the P removed during the rotation experiment has been over-estimated. The 'error' is less than 1 lb P/acre each year, probably no worse than actual analyses of all crops would have given. However, whereas crop analyses would have positive and negative errors, any errors in our calculations have apparently always overestimated the amount of P removed.

Potassium. Fig. 8 shows that both the yield of dry grass and the K removed by the grass were not well related to exchangeable soil K, either during the first two years (Fig. 8a and b) or from 1958–63 (Fig. 8c and d). Table 11 shows the amount of exchangeable K in the 0–9 in. depth of soil on five sampling occasions; there are some unexplained anomalies in the 1969 samples, possibly sampling error. On average the amounts of exchangeable K in the unmanured soils changed little between 1958 and 1970 though 670 and 760 lb K/acre were removed from these soils by the grass. Table 12 shows that an extra 412–715 lb K/acre was removed by the grass from plots with residues and the amount of exchangeable K decreased (Table 11) but the two were not related.

TABLE 11

Amounts of soluble-K in the soils of the Agdell grass experiment, 1958–69

		K, ppm, soluble in 1*N*-ammonium acetate Soils, 0–9 in. deep, not given new K in 1964				
Plot	Treatment 1848–1951	1958	1961	1964	1967	1969
1	NPK—fallow	176	105	101	116	136
2	NPK—clover	130	81	108	100	114
3	PK—fallow	175	124	103	131	126
4	PK—clover	158	105	111	112	129
5	None—fallow	102	94	97	91	103
6	None—clover	128	123	119	110	112

We intend to investigate further why both crop yield and K removed by grass in this experiment were not closely correlated with the initially exchangeable K in the soil, either for a short or long period of cropping. We expected a better correlation than we found especially as we have shown that the amount of residues remaining in the soils from the rotation experiment is correlated with their contents of exchangeable K. Also, when Arnold and Close (1961) exhaustively cropped samples of the surface soils (0–9 in.)

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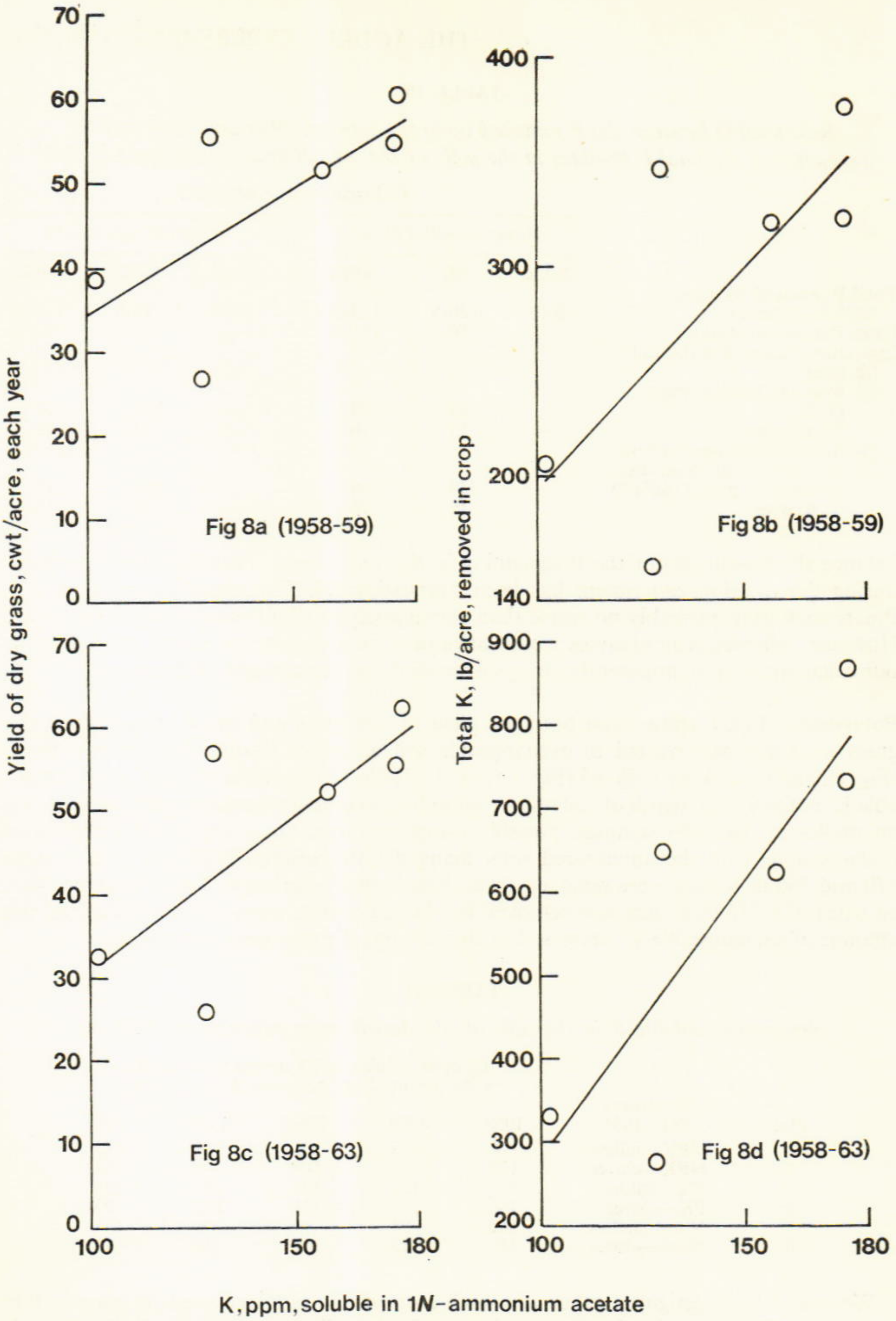

FIG. 8. Relationship between both yield of dry grass (cwt/acre) and K (lb/acre) removed in the grass and K soluble in 1N-ammonium acetate in the 0–9 in. depth of soil in 1958 on Agdell Field, Rothamsted.

(a) Mean annual yield 1958–59 and soluble-K in soil.
(b) Total K removed 1958–59 and soluble-K in soil.
(c) Mean annual yield 1958–63 and soluble-K in soil.
(d) Total K removed 1958–63 and soluble-K in soil.

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TABLE 12

Relationship between the K removed by grass between 1958 and 1970 and the estimate of the K residue in the soils of the Agdell grass experiment in 1958

	Old treatments, 1848–1951					
	Rotation with fallow			Rotation with clover		
	None	PK	NPK	None	PK	NPK
Total K removed by grass, 1958–70 (lb/acre)	765	1276	1480	675	1253	1087
Extra K from the residues	—	511	715	—	587	412
Estimates of extra K in the soil (lb/acre)						
(a) from the balance sheet (Table 1)	—	1406	1289	—	531	703
% recovery	—	36	55	—	109	59
(b) from the analyses for exchangeable K in the soil (0–18 in. deep) (Table 2)	—	277	268	—	146	170
% recovery	—	184	267	—	396	242

from these Agdell plots with ryegrass in pots, they found that the K removed was well related to initially exchangeable K, even though the grass also removed much initially non-exchangeable K. Arnold and Close also calculated from their results the equivalent amount of extra K/acre removed from the surface soils of plots with residues. The amounts are much less than our estimates of the amounts of the residues and in this respect their results confirm our deduction that some of the K residues have been 'lost'. In the field factors other than the amount of exchangeable K or the amount of residues influence the amount of K available to a crop. Obviously the release of soil K is important but probably not as important as the relative amounts of topsoil and subsoil and their contents of available K which can be explored by crop roots.

Conclusions and future work

The amounts of P and K accumulated in the Agdell soils from fertiliser dressings were much smaller than in some other Classical experiments at Rothamsted. However, an estimate of the residues derived from the gains and losses of P and K between 1848 and 1958 were correlated with the results of analyses of the 0–18 in. depth of soil for total- and bicarbonate soluble-P and exchangeable K. In 1958 half of each rotation plot was sown with grass, with two objectives; the first was to find the value of the residues for grass and whether grass given much N could exhaust them; the second was to increase the organic matter of the soils so that arable crops could later be grown on soils containing similar amounts of P and K but different amounts of organic matter. The experiment was modified in 1964 when the half plots were further divided to test new dressings of both P and K.

Grass behaved much as arable crops grown on this soil. Residues not only increased yields but did so even when fresh dressings of P and K were given. The reason for this is not clear, but in addition to providing nutrients well distributed throughout the cultivated layer, soils may have better physical properties when they have long produced large crops than when they have produced poor ones. P residues were recovered at a fairly constant rate during 12 years and probably all the residues would have been recovered had the experiment continued long enough. In contrast, it seems improbable that all the K residues will be recoverable, possibly because they have been leached too deeply or because they are released no faster than 'native' soil K. This suggests that over-generous K manuring may lose some K. Thus in practice it may be important when

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manuring with K to balance the K requirement of the crop, and pay regard to the amount the soil may release during the growth of the crop.

Much work has been done in other experiments to relate crop responses to new fertiliser with soil analyses. Too often the results have not been encouraging, because many sites in different localities were needed to get a range of soil values large enough to test each method of analysis. However, soluble soil-P and -K probably do not change considerably from year to year, and weather and management are much more variable. To examine the value of soil analysis in well-defined conditions, this experiment was modified in 1964. At two amounts of soil organic matter, it provides 24 soils containing different amounts of both bicarbonate soluble-P and exchangeable K. Using a rotation of three arable crops, we hope to define the minimum amounts of soil P and K at which the crops would not be expected to respond to new dressings of P and K. This information will then be used to modify the P and K manuring on those fields on Rothamsted farm used for experiments other than those testing P and K. This work is also being extended by similar experiments at Woburn and Saxmundham.

Summary

1. The four-course rotation experiment on Agdell Field from 1848–1951 compared a legume or a fallow in the third year: roots, barley, legume or fallow, winter wheat. Three manurial treatments were tested, unmanured, PKNaMg, NPKNaMg; the manures were given to the root crop only. About 140 lb N was given as a mixture of ammonium salts and rape cake. The initial superphosphate dressing supplied 30 lb P/acre but later ones 38 lb P; the rape cake supplied 20 lb P/dressing. Fertiliser K was also increased during the experiment, from 120 to 200 lb K/acre, but the rape cake always supplied about 20 lb K/acre. Dressings of sodium, 14 lb Na, and magnesium, 10 lb Mg/acre, were small.

2. A nutrient balance made for P and K showed that the amounts that accumulated in the soil depended not only on the manuring but also on the crop rotation, especially for K because of the amount removed by clover.

3. Total soil P, soil P soluble in 0·5M–$NaHCO_3$ and exchangeable K were linearly related to the estimates of the balance between P and K removed in the crops and the gains from fertiliser dressings. These relationships are compared with others for experiments at Saxmundham and Rothamsted. Were losses and gains exactly balanced, both soils would contain 9 ppm of bicarbonate soluble-P and 140–160 ppm of exchangeable K.

4. Grass was grown from 1958 to 1970 on half-plots of the rotation experiment; it had to be resown in spring 1960 and 1964 and autumn 1967. It was always cut at silage stage and 0·8 cwt N/acre was given for every cut. Between 1958 and 1963, P and K were not given and the combined effects of P and K residues were measured. From 1964–70, P was given to sub-plots testing K, and K to sub-plots testing P residues, to measure their effects separately. In 1964 new dressings of P (0, 4, 8, 16 cwt P_2O_5 plus 10 cwt K_2O/acre) and of K (0, 2·5, 5·0, 10 cwt K_2O plus 16 cwt P_2O_5/acre) were also tested on sub-plots. To maintain differences in soil P and K between sub-plots, the P and K removed in the grass were replaced by equivalent amounts of P and K as fertilisers, except on sub-plots P_0K_4 and P_4K_0 which got no P and no K respectively.

5. The residues always had large effects on the newly sown grass. These effects were smaller after the grass was well established, but obtained even when new dressings of P and K were given. Without such new dressings, clover-rotation plots always yielded less than corresponding fallow-rotation plots, because of the P and K removed by the clover

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during the 'Classical' period. Yields were increased more by P residues than by K residues.

6. Although most of the response to new P and K was to the smallest dressing given, 4 cwt P_2O_5, 2·5 cwt K_2O/acre, the largest dressings, 16 cwt P_2O_5, 10 cwt K_2O/acre, did not decrease yields.

7. The grass always removed more P and K from the fallow- than from the clover-rotation plots.

8. On average, 4 lb P/acre was removed each year from the starved soils and 9–13 lb P/acre from the soils with residues. The grass recovered 18–20% of the P residues during 12 years, and the rate of recovery was similar during both six-year periods. An extra 10 lb P/acre was removed each year from the smallest dressing of new P given, irrespective of the size of the residues; little further was taken up from the larger dressings.

9. On average, 55 lb K/acre was removed from the starved soils each year; when little K was removed during any year because the crop was small, extra K was removed during the next year. During the first six years, 110–150 lb K/acre was removed each year from soils containing residues, and 30–70% of the estimated total was recovered. During the second six years, the annual recovery was only 6–30 lb K/acre. Over the whole period, the larger the amount of the estimated K residues, the smaller was the percentage recovered. This suggests that either some of the K residues had leached to a depth below which the grass could not recover it, or it had become fixed in such a manner that it was released at a similar rate to 'native' soil K. An extra 100 lb K/acre was removed each year from the smallest new dressing given, and a further 20–40 lb K/acre from the larger dressings.

10. Both the yield of dry grass and the P it removed were correlated with the amount of bicarbonate soluble-P in the soil. Amounts of bicarbonate soluble-P changed little on the starved soils during 12 years, but they decreased in plots containing residues.

11. The yield of dry grass and K removed were less well correlated with the amounts of exchangeable K in the soil. On the starved plots, there was little change in exchangeable K content even though 670 and 760 lb K/acre were removed during 12 years. On the plots with residues, the exchangeable K contents decreased to those on starved soils without all the estimated K residues being recovered.

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APPENDIX TABLE 1

Mean annual yield of dry matter (lb/acre) of the crops grown in the Agdell rotation experiment, 1848–1951

			Rotation with fallow			Rotation with clover			Rotation with fallow			Rotation with clover		
Course	Years		None	PK	NPK	None	PK	NPK	None	PK	NPK	None	PK	NPK
			Turnip roots						Turnip tops					
1	1848–51	—	2392	3984	4827	1172	2764	2610	444	670	870	1217	1814	2876
2–9	1852–83	—	341	1821	3094	216	1766	3098	54	170	321	47	188	356
10–13	1884–99	—	256	2422	4828	113	2796	4544	80	209	546	39	255	591
14–18	1900–19	—	287	2118	4806	97	2769	3549	62	149	501	29	214	478
19–22	1920–35	—	223	1405	2360	72	1861	1433	115	348	703	29	470	462
23–26	1936–51	—	124	768	701	35	808	478	89	249	230	28	244	173
			Barley grain						Barley straw					
1	1848–51	—	1892	1728	1983	2254	1756	1768	2152	2117	2716	2573	2212	2332
2–9	1852–83	—	1397	1474	2089	1398	1537	2130	1490	1536	2365	1553	1617	2371
10–13	1884–99	—	794	760	1164	640	1169	1482	1085	972	1728	963	1440	1948
14–18	1900–19	—	745	898	1083	705	1095	1488	908	1091	1260	945	1299	1710
19–22	1920–35	—	491	600	473	297	838	817	722	786	729	681	1097	1313
23–26	1936–51	—	823	1374	1475	611	1510	1082	1025	1580	1598	979	1751	1804
			Clover hay											
1	1848–51	1 clover crop	5720	5921	6554	5428	5181	5952						
2–9	1852–83	2 clover crops	—	—	—	2152	5181	6774						
10–13	1884–99	2 clover crops	—	—	—	868	3753	3766						
14–18	1900–19	5 clover crops	—	—	—	633	2434	1380						
19–22	1920–35	3 clover crops	—	—	—	2017	2488	711						
23–26	1936–51	4 clover crops	—	—	—	1008	3312	1716						
			Bean grain						Bean straw					
2–9	1852–83	6 bean crops	—	—	—	628	706	1294	—	—	—	857	1096	1514
10–13	1884–99	2 bean crops	—	—	—	928	1638	1166	—	—	—	810	1566	1062
19–22	1920–35	1 bean crop	—	—	—	527	1430	762	—	—	—	964	2599	1515
			Winter wheat grain						Winter wheat straw					
1	1848–51	—	1735	1836	1628	1708	1702	1724	2924	3140	3220	3076	3162	3248
2–9	1852–83	—	1500	1669	1642	1302	1591	1746	2605	2932	3216	2166	2642	3162
10–13	1884–99	—	1516	1860	2018	1426	2222	2203	2183	2867	3220	1958	3168	3213
14–18	1900–19	—	832	1149	1286	863	1456	1223	1616	2310	2427	1625	2919	2195
19–22	1920–35	—	820	901	667	874	986	812	1745	2443	1771	1914	2586	2038
23–26	1936–51	—	1393	1844	1588	1132	1860	1844	2294	2926	2537	1940	3092	2851

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APPENDIX TABLE 2

Mean annual amount of P (lb/acre) removed in the crops grown in the Agdell rotation experiment, 1848–1951

Course	Years	Rotation with fallow			Rotation with clover			Rotation with fallow			Rotation with clover		
		None	PK	NPK	None	PK	NPK	None	PK	NPK	None	PK	NPK
		Turnip roots						Turnip tops					
1	1848–51	3·64	7·97	11·87	1·73	5·61	6·26	0·98	2·24	3·47	2·85	6·46	11·16
2–9	1852–83	0·52	3·65	7·60	0·32	3·59	7·45	0·12	0·57	1·28	0·11	0·67	1·38
10–13	1884–99	0·39	4·84	11·88	0·17	5·68	10·90	0·18	0·70	2·18	0·09	0·91	2·29
14–18	1900–19	0·44	4·24	11·82	0·14	5·62	8·52	0·14	0·50	2·00	0·07	0·76	1·85
19–22	1920–35	0·34	2·81	5·80	0·11	3·78	3·44	0·26	1·16	2·80	0·07	1·67	1·79
23–26	1936–51	0·19	1·54	1·72	0·05	1·64	1·15	0·20	0·83	0·92	0·07	0·87	0·67
		Barley grain						Barley straw					
1	1848–51	6·58	7·10	8·15	7·55	6·99	7·16	1·16	1·23	1·63	1·36	1·26	1·40
2–9	1852–83	4·86	6·06	8·59	4·69	6·12	8·62	0·80	0·90	1·42	0·82	0·92	1·42
10–13	1884–99	2·76	3·12	4·78	2·14	4·65	6·00	0·58	0·56	1·04	0·51	0·82	1·17
14–18	1900–19	2·59	3·69	4·45	2·36	4·36	6·03	0·49	0·63	0·76	0·50	0·74	1·03
19–22	1920–35	1·71	2·47	1·94	1·00	3·34	3·31	0·39	0·46	0·44	0·36	0·62	0·79
23–26	1936–51	2·86	5·65	6·06	2·21	6·01	4·38	0·55	0·92	0·96	0·52	1·00	1·08
		Clover hay											
1	1848–51	8·69	10·78	13·89	8·25	9·44	12·62						
2–9	1852–83	—	—	—	3·27	9·44	14·40						
10–13	1884–99	—	—	—	1·32	6·83	7·98						
14–18	1900–19	—	—	—	0·96	4·43	2·92						
19–22	1920–35	—	—	—	3·06	4·53	1·51						
23–26	1936–51	—	—	—	1·53	6·03	3·64						
		Bean grain						Bean straw					
2–9	1852–83	—	—	—	2·24	3·27	5·36	—	—	—	0·51	0·82	0·88
10–13	1884–99	—	—	—	3·31	7·60	4·83	—	—	—	0·49	1·17	0·62
19–22	1920–35	—	—	—	1·88	6·64	3·15	—	—	—	0·58	1·95	0·88
		Winter wheat grain						Winter wheat straw					
1	1848–51	6·25	7·00	6·43	6·20	6·89	7·08	1·37	1·79	2·16	1·63	2·02	2·40
2–9	1852–83	5·40	6·36	6·48	4·73	6·44	7·18	1·22	1·68	2·17	1·14	1·68	2·35
10–13	1884–99	5·46	7·09	7·97	5·18	9·00	9·05	1·03	1·63	2·16	1·04	2·03	2·38
14–18	1900–19	3·00	4·38	5·08	3·13	5·90	5·03	0·76	1·32	1·63	0·86	1·87	1·62
19–22	1920–35	2·95	3·43	2·63	3·17	3·99	3·34	0·82	1·39	1·19	1·01	1·66	1·51
23–26	1936–51	5·01	7·02	6·27	4·11	7·53	7·58	1·08	1·67	1·70	1·03	1·98	2·11

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APPENDIX TABLE 3

Mean annual amount of K (lb/acre) removed in the crops grown in the Agdell rotation experiment, 1848–1951

		Rotation with fallow			Rotation with clover			Rotation with fallow			Rotation with clover		
Course	Years	None	PK	NPK	None	PK	NPK	None	PK	NPK	None	PK	NPK
		Turnip roots						Turnip tops					
1	1848–51	27·3	43·0	89·8	13·1	30·1	47·8	7·2	8·8	20·9	20·2	25·2	69·0
2–9	1852–83	3·9	19·7	57·7	2·4	19·3	56·7	0·9	2·2	7·7	0·8	2·6	8·5
10–13	1884–99	2·9	26·6	89·8	1·3	30·7	83·1	1·3	3·1	13·1	0·6	3·8	14·2
14–18	1900–19	3·3	23·3	89·4	1·1	30·4	64·9	1·0	2·2	12·0	0·5	3·2	11·5
19–22	1920–35	2·5	15·4	43·9	0·8	20·5	26·2	1·9	5·2	16·9	0·5	7·0	11·1
23–26	1936–51	1·4	8·4	13·0	0·4	8·9	8·7	1·4	3·7	5·5	0·5	3·7	4·2
		Barley grain						Barley straw					
1	1848–51	9·1	9·0	10·5	10·4	8·8	9·2	12·7	12·3	19·8	14·9	12·4	17·2
2–9	1852–83	6·7	7·6	11·0	6·4	7·7	11·0	8·9	8·9	17·4	9·1	9·2	17·6
10–13	1884–99	3·8	4·0	6·2	2·9	5·8	7·7	6·4	5·8	12·6	5·6	8·6	14·4
14–18	1900–19	3·6	4·7	5·7	3·2	5·5	7·7	5·4	6·5	9·2	5·5	7·8	12·6
19–22	1920–35	2·4	3·1	2·5	1·4	4·2	4·2	4·2	4·7	5·3	3·9	6·6	9·7
23–26	1936–51	4·0	7·1	7·8	3·0	7·6	5·6	6·0	9·5	11·7	5·7	10·5	13·3
		Clover hay											
1	1848–51	70·3	58·6	102·9	66·8	51·3	93·4						
2–9	1852–83	—	—	—	26·5	51·1	106·1						
10–13	1884–99	—	—	—	10·7	48·8	59·1						
14–18	1900–19	—	—	—	7·8	31·6	21·7						
19–22	1920–35	—	—	—	24·8	32·3	11·2						
23–26	1936–51	—	—	—	12·4	43·0	26·9						
		Bean grain						Bean straw					
2–9	1852–83	—	—	—	6·0	6·7	13·5	—	—	—	2·4	3·1	5·9
10–13	1884–99	—	—	—	8·9	16·4	12·1	—	—	—	2·3	5·5	4·1
19–22	1920–35	—	—	—	5·0	14·3	7·9	—	—	—	2·7	9·1	5·9
		Winter wheat grain						Winter wheat straw					
1	1848–51	8·2	8·8	8·0	8·4	8·7	8·8	17·5	18·2	21·6	20·3	19·6	23·4
2–9	1852–83	7·1	8·0	8·1	6·4	8·1	9·0	15·5	16·9	21·6	14·2	16·3	22·7
10–13	1884–99	7·1	8·9	9·9	7·0	11·3	11·2	13·1	18·6	21·6	12·9	20·6	23·1
14–18	1900–19	3·9	5·5	6·3	4·2	7·4	6·2	9·7	15·0	16·3	10·7	19·0	15·8
19–22	1920–35	3·8	4·3	3·3	4·3	5·0	4·1	10·5	15·9	11·9	12·6	16·8	14·7
23–26	1936–51	6·5	8·8	7·8	5·5	9·5	9·4	13·8	19·0	17·0	12·8	20·1	20·5

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APPENDIX TABLE 4

Yields (cwt/acre) of dry Timothy (S51) 1964–67

New treatments, 1964		Old treatments, 1848–1951					
		Rotation with fallow			Rotation with clover		
P	K	None	PK	NPK	None	PK	NPK
				1964 (1 cut)			
0	4	0·0	0·9	7·0	0·0	2·0	3·5
1	4	6·3	8·6	13·2	7·8	8·0	12·2
2	4	6·0	9·1	15·9	6·1	10·5	15·3
4	4	8·6	11·5	18·7	8·2	10·4	18·9
4	0	3·0	4·0	8·8	3·2	6·6	8·8
4	1	7·1	7·4	16·7	8·3	11·9	16·6
4	2	5·4	13·3	16·3	11·7	15·3	16·4
4	4	7·5	7·2	16·2	10·0	14·7	19·6
				1965 (3 cuts)			
0	4	83·1	85·8	108·5	56·6	84·1	92·1
1	4	93·2	103·9	113·7	98·6	80·6	98·9
2	4	95·4	95·9	108·9	97·8	85·3	97·7
4	4	99·5	102·2	117·0	102·0	88·6	97·5
4	0	88·8	86·6	97·1	90·4	88·9	87·3
4	1	85·7	104·7	97·1	92·1	95·6	98·1
4	2	87·3	100·3	96·6	90·3	95·2	93·9
4	4	93·2	102·9	106·7	92·9	93·4	104·0
				1966 (4 cuts)			
0	4	43·2	68·7	92·6	29·0	65·9	75·9
1	4	83·9	89·0	100·8	83·6	90·7	96·2
2	4	92·1	89·9	101·8	97·2	79·5	92·1
4	4	91·7	98·4	93·5	95·8	96·3	90·2
4	0	59·4	74·8	88·6	55·8	81·3	60·7
4	1	91·1	89·0	103·5	94·8	94·2	94·3
4	2	92·1	92·9	93·2	83·7	91·5	88·9
4	4	102·2	86·3	95·7	97·1	94·0	96·4
				1967 (1 cut)			
0	4	13·7	30·2	37·0	7·9	17·0	27·1
1	4	50·4	48·6	45·2	47·8	47·0	46·4
2	4	55·8	42·4	39·0	45·4	39·3	53·6
4	4	46·9	48·4	42·9	44·9	48·2	40·4
4	0	41·7	24·1	26·2	23·9	37·8	25·5
4	1	57·6	38·4	41·7	44·3	47·3	48·1
4	2	53·0	36·8	45·4	43·4	44·7	49·0
4	4	53·6	38·8	46·6	46·2	37·3	48·9

P_0 = no phosphate P_1 = 4 cwt P_2O_5/acre P_2 = 8 cwt P_2O_5/acre P_4 = 16 cwt P_2O_5/acre
K_0 = no potash K_1 = $2\frac{1}{2}$ cwt K_2O/acre K_2 = 5 cwt K_2O/acre K_4 = 10 cwt K_2O/acre

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APPENDIX TABLE 5

Yields (cwt/acre) of dry Timothy (S51), 1968–70

New treatments, 1964		Old treatments, 1848–1951: Rotation with fallow			Rotation with clover		
P	K	None	PK	NPK	None	PK	NPK
				1968 (3 cuts)			
0	4	23·3	44·6	64·7	26·2	32·8	46·0
1	4	69·3	78·5	86·8	72·9	83·4	82·7
2	4	72·0	80·7	75·2	81·4	75·6	88·4
4	4	73·0	78·1	84·0	73·2	75·3	85·6
4	0	56·4	67·1	57·8	65·3	71·6	53·0
4	1	71·5	76·2	80·5	74·6	87·5	84·2
4	2	75·7	71·3	85·9	82·5	78·6	86·7
4	4	80·3	76·3	82·4	72·4	86·1	84·3
				1969 (3 cuts)			
0	4	36·3	61·2	75·0	28·2	41·8	72·7
1	4	70·1	72·2	82·7	66·0	85·8	78·4
2	4	71·2	77·1	90·2	68·8	68·6	83·4
4	4	74·0	69·7	81·0	69·5	88·1	88·2
4	0	54·2	58·4	65·4	40·5	72·9	53·2
4	1	70·6	72·4	75·8	78·3	80·0	77·6
4	2	68·1	66·0	79·4	74·2	67·9	87·0
4	4	68·5	74·1	91·0	75·9	83·3	85·2
				1970 (2 cuts)			
0	4	—	—	—	—	—	—
1	4	—	—	—	—	—	—
2	4	—	—	—	—	—	—
4	4	—	—	—	—	—	—
4	0	18·1	28·1	31·9	18·8	26·4	19·0
4	1	47·1	45·8	51·9	53·8	53·3	54·6
4	2	45·9	49·7	51·4	55·9	53·2	66·6
4	4	47·2	50·3	49·8	51·0	55·6	59·4

P_0 = no phosphate $\quad$ P_1 = 4 cwt P_2O_5/acre $\quad$ P_2 = 8 cwt P_2O_5/acre $\quad$ P_4 = 16 cwt P_2O_5/acre

K_0 = no potash $\quad$ K_1 = $2\frac{1}{2}$ cwt K_2O/acre $\quad$ K_2 = 5 cwt K_2O/acre $\quad$ K_4 = 10 cwt K_2O/acre

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APPENDIX TABLE 6

Amounts of P and K removed each year by the grass grown on Agdell, Rothamsted 1964–70

P (lb/acre) removed from P test sub-plots								K (lb/acre) removed from K test sub-plots							
New treatments, 1964		Old treatments, 1848–1951						New treatments, 1964		Old treatments, 1848–1951					
		Rotation with fallow			Rotation with clover					Rotation with fallow			Rotation with clover		
P	K	None	PK	NPK	None	PK	NPK	P	K	None	PK	NPK	None	PK	NPK
		1964 (1 cut)								1964 (1 cut)					
0	4	0	0·2	1·3	0	0·4	0·6	4	0	4	6	14	4	10	12
1	4	1·1	1·6	2·3	1·1	1·6	2·1	4	1	12	17	36	16	26	35
2	4	1·1	1·7	3·0	1·1	2·0	2·9	4	2	10	30	38	22	34	37
4	4	1·8	2·4	3·9	1·5	2·1	3·7	4	4	16	18	41	20	37	46
		1965 (3 cuts)								1965 (3 cuts)					
0	4	17·3	23·7	30·1	7·2	16·4	21·2	4	0	129	174	205	138	197	144
1	4	29·6	38·6	49·4	31·8	26·1	34·1	4	1	231	287	263	242	268	237
2	4	34·3	38·9	55·2	35·6	31·7	37·4	4	2	260	302	277	259	270	298
4	4	38·4	47·8	52·4	40·0	34·2	39·3	4	4	282	323	339	275	309	362
		1966 (4 cuts)								1966 (4 cuts)					
0	4	6·3	12·3	22·0	3·8	11·0	13·7	4	0	68	104	130	66	114	74
1	4	24·1	33·1	34·2	23·6	26·2	31·0	4	1	217	236	253	242	216	208
2	4	28·5	32·6	38·8	32·6	27·2	33·8	4	2	251	250	252	207	265	229
4	4	33·3	41·1	41·4	35·7	37·2	36·9	4	4	358	297	316	328	324	303
		1967 (1 cut)								1967 (1 cut)					
0	4	2·0	5·7	9·2	0·9	2·5	5·0	4	0	58	35	44	29	58	41
1	4	14·6	19·0	17·4	14·9	13·5	17·6	4	1	182	128	138	142	139	151
2	4	15·2	15·7	15·7	15·0	13·3	19·8	4	2	180	126	167	143	155	156
4	4	14·6	20·3	17·3	16·1	16·0	15·1	4	4	186	142	154	152	143	171
		1968 (3 cuts)								1968 (3 cuts)					
0	4	3·2	7·2	13·5	3·3	5·2	7·9	4	0	75	111	90	91	118	76
1	4	14·9	21·9	23·5	17·4	21·4	21·4	4	1	204	236	245	226	265	248
2	4	18·3	23·9	21·8	17·0	21·6	25·7	4	2	237	222	281	234	256	268
4	4	21·2	25·7	27·9	22·4	23·5	26·2	4	4	260	253	284	231	288	268
		1969 (3 cuts)								1969 (3 cuts)					
0	4	5·0	10·3	15·0	4·0	7·0	12·0	4	0	79	82	93	52	108	73
1	4	14·3	17·2	20·2	15·2	19·8	17·4	4	1	182	221	220	211	229	205
2	4	16·7	19·3	21·5	17·6	17·4	21·0	4	2	195	203	241	204	204	270
4	4	19·0	18·9	23·0	17·6	22·1	23·0	4	4	208	235	287	228	258	261
										1970 (2 cuts)					
								4	0	20	33	39	19	25	19
								4	1	124	150	142	151	160	146
								4	2	136	153	172	146	162	197
								4	4	160	176	173	147	186	194